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Artisanal gold mining in Antioquia, Colombia: a successful case of mercury reduction

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ABSTRACT

Five municipalities in Antioquia, Colombia, with population of 162,000 inhabitants, were the world's largest mercury polluter from artisanal gold mining in 2010, releasing and emitting an average of 92 (73–110) tonnes/a of mercury. UNIDO – United Nations Industrial Development Organization joined forces with the Government of Antioquia, National University of Colombia and University of British Columbia to start The Colombia Mercury Project to reduce mercury use and losses.[1] The actions consisted of assessment of mercury losses, health monitoring and awareness campaign. This was supported by technical demonstrations of methods to reduce the amount of mercury used in the processing centres ("entables"). Enhanced enforcement of existing local and federal regulations accompanied these activities. Demonstrations of cleaner methods to miners and owners of "entables" generated 39 new mercury-free processing plants. The presence of the company Gran Colombia Gold buying ore from the miners at a fair price also contributed considerably to observed reductions in mercury use. Mercury entering in the whole ore amalgamation in the 323 "entables" was reduced on average 43% from 2010 levels. In 2013, mercury losses were reduced by 63%, resulting in **46 to 70 tonnes/a**, less mercury entering the environment than in 2010.

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1. Artisanal gold mining and mercury

Artisanal mining is characterized by rudimentary extraction methods (Veiga, 1997). In more than 70 developing countries, there are 30 million individuals extracting more than 30 different minerals artisanally (Veiga et al., 2014a). As the price of gold tripled in the last 10 years, the number of artisanal gold miners increased substantially in the rural areas all over the world. Around 16 million people are directly involved in this activity, producing 380–450 tonnes of gold annually (Seccatore et al., 2014), and releasing and emitting 1400 tonnes/a of mercury to land, water, and air (UNEP, 2013a). According to UNEP (2013b), artisanal gold mining is the largest source of anthropogenic mercury emissions (727 tonnes/a).

Jønsson et al. (2013) suggest possible explanations for the fact that artisanal miners continue to use mercury haphazardly and underrate its health impacts, and discuss possible ways to facilitate mercury reduction. While Clifford (2014) acknowledges that there are some positive signs that academics and policymakers are reaching a new consensus on how to tackle the issue more effectively, he advocates more 'humanistic' reconceptualisations of approaches to mercury pollution in the sector. Spiegel et al. (2014) outline possible ways to address intertwined technological, political and socio-economic challenges facing marginalized populations in mining communities. They stress the need for international donors and national policymakers proactively engage—rather than vilify—artisanal miners, and for gender-sensitive grassroots empowerment initiatives. These analyses all underscore the need for fundamentally reforming national mining policy priorities, recognizing marginalized mining communities' resource rights and tackling livelihood insecurity. Formalization of artisanal miners is not enough to guarantee cleaner procedures. Demonstration of simple techniques can obtain extraordinary results if the miners are engaged in all steps of the educational process (Veiga et al., 2014b).

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[1] Mercury loss = emission (to air) + release (to water and land).

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2. Artisanal gold miners in Antioquia

Despite the regulations on artisanal mining in Colombia, the sector has a large number of informal and illegal miners due to poor law enforcement in rural areas. According to Guiza and Aristizabal (2013), 87% of 4134 Colombian gold mining operations are illegal and 95% of all the gold mines have no environmental permit. In 2013, Colombia officially produced 55.74 tonnes of gold (America Economia, 2014). The artisanal and small-scale sector produced 72% of the country's gold or around 40 tonnes/a of gold in which 66% were illegal (Guiza, 2013). According to the Ministry of Energy and Mines there are 1526 gold mines in the Department of Antioquia, of which 186 have legal mineral titles (12.2%) which is much higher than the national formalization (legalization of informal and illegal miners) level. The Colombian Government's efforts to formalize artisanal miners resulted in a modest 1% of formalization by 2008 in the whole country, though formality rates are also low in other productive industries in the Colombian economy. About 60% of the population, not including those involved in agricultural activities, is employed in the informal sector (ILO, 2012). About 37.2% (Index Mundi, 2012) of Colombia's 47 million residents live below the national poverty line and 25.5% of Colombians live in rural areas, (Trading Economics, 2012), where poverty is most prevalent. In 2009, 64% of the rural population or more than 7.7 million people were poor, and 2 million lived in extreme poverty (IFAD, 2012).

Guiza and Aristizabal (2013) highlighted the discrepancy between the official numbers of artisanal gold miners in Colombia and the field observations. From 2009 to 2011, the Government of Colombia conducted a Mining Census in twenty-three Departments (Colombian Provinces) and concluded that there are approximately 50,000 artisanal gold miners in the country whereas Cordy et al. (2011) estimated around 200,000 miners, based on data from neighbouring countries and the gold production observed in the field. The higher estimate was corroborated by the Secretary of Mines of Antioquia (Veiga et al., 2014a).

In the Department of Antioquia (Fig. 1), it is estimated that there are 15,000 to 30,000 artisanal gold miners, most of them are located in the Lower Cauca River and in the Northeast region of Antioquia where gold has been mined since pre-colonial times (Veiga, 2010). The majority of Antioquia's gold production comes from 5 municipalities: Segovia, Remedios, Zaragoza, El Bagre and Nechi with population of 162,000 inhabitants. In 1852, the company, Frontino Gold Mine was established in the town of Segovia and in the 19th century, Colombia became the largest gold producer in the world (Kline, 2012). Today, Segovia (population: 37,000) is still the largest gold-producing town in the country due to the presence of Gran Colombia Gold (GCG), a Canadian-based company, which began operations in 2011. Gran Colombia owns the largest underground gold mine in Colombia and has 21,400 ha of mineral titles in the region. The company estimated a reserve of 5 million troy ounces (oz) of gold at an average production grade of 9.3 g/t in which around 110,000 oz (3.42 tonnes) of Au were produced in 2013, with plans to increase production, in a near future, to 200,000 oz (6.22 tonnes). Since 2005, the company works in

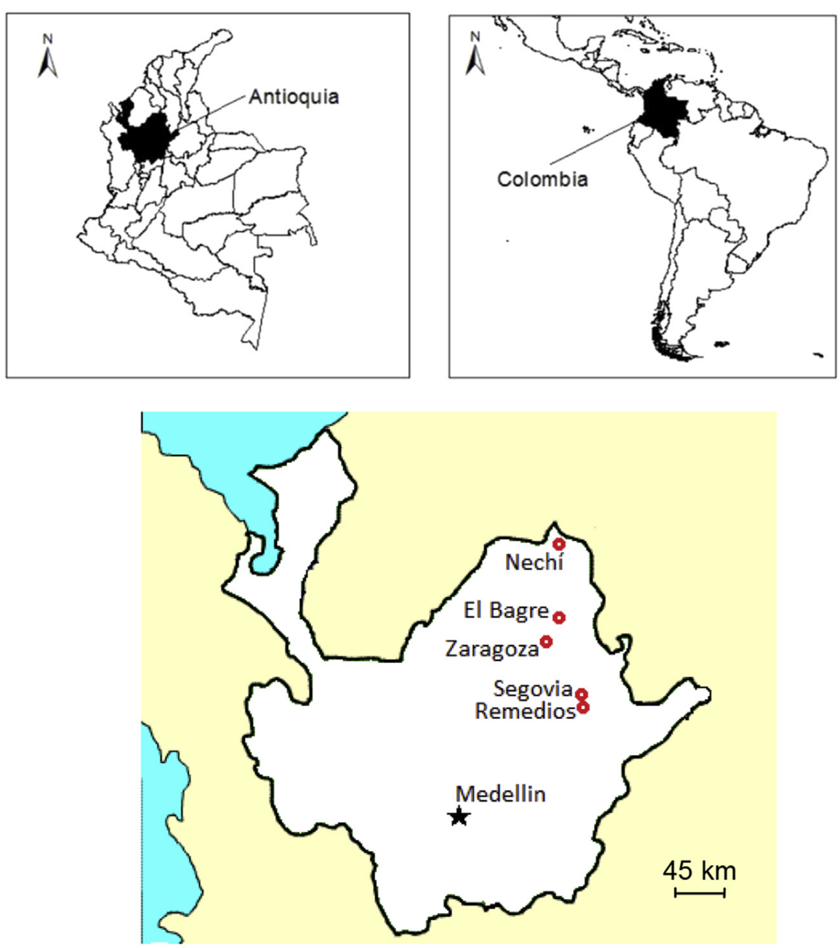

Fig. 1. Map of the Department of Antioquia indicating the 5 municipalities considered in this study.

partnership with approximately 4000 artisanal miners (Gran Colombia Gold, 2014). This has reduced conflicts with the artisanal miners and the use of mercury.

3. "Entables", where the mercury pollution is generated

Due to the past actions of guerrilla groups in rural areas of Antioquia, artisanal gold processing facilities were established in urban centres due to their relative safety. Miners extract gold ore for 3 weeks and bring 18–40 tonnes of ore to be processed in one of the 323 gold processing centres (locally known as "entables") in the 5 municipalities studied in Antioquia. The whole ore is amalgamated in small ball mills ("cocos") without first concentrating the gold to reduce the amount of material exposed to mercury (Fig. 2). In the 5 municipalities in 2010, there were approximately 2600 "cocos" in the 5 target municipalities. The large majority of the "cocos" are very similar. About 60–70 kg of ore is added to each "coco" with about 80 g of mercury (in 2010). The mill runs for 4 h, after which the amalgam is separated from the rest of the minerals by panning, and the excess liquid mercury is squeezed out in a piece of cloth, resulting in a solid ball of amalgam containing 40–50% mercury and 50–60% gold and silver. Amalgam produced in the "entables" is given to the miners from whose ore it was processed, and the miners then sell it to one of the 98 gold shops in the 5 municipalities. Mercury from amalgam is evaporated with a propane torch without any condenser or filter, releasing the vapours to the urban environment and leaving behind gold–silver. The Hg-contaminated tailings from the "cocos" are collected and subjected to cyanidation by the owners of the "entables". Miners usually do not need to pay for the amalgamation service but sometimes a nominal fee of US$ 1 per coco is charged. Miners receive less than 40% of the gold in their ore.

The cyanidation process recovers less than 80% of the residual gold from the tailings. This is usually conducted in static percolation tanks and the gold-loaded solution passes through PVC columns filled with zinc shavings where gold is precipitated. Residual mercury in the tailings is also leached by the cyanide solution and precipitated on the zinc shaving. When the shavings turn dark brown, the miners stop the leaching process, transfer the shavings to a steel bucket and introduce it into a gas furnace at 910 °C. This evaporates the zinc and mercury associated with the shavings leaving behind gold and silver (Fig. 3). A similar procedure has been observed in Ecuador (Velasquez-Lopez et al., 2011). Without any condenser or protection for the operators and neighbours of the "entables", this is clearly a health hazard. After the evaporation process, the residue in the bucket rich in gold and silver is leached with nitric acid to remove excess zinc and separate silver from gold.

Fig. 2. "Cocos" are small ball mills to amalgamate the whole ore.

In 2010, the town of Segovia alone was releasing and emitting to the environment 22.4 tonnes/a of mercury. Mercury consumed (and lost) by "entables" in the 5 Antioquia municipalities was estimated to be between 73 and 110 tonnes in 2010. The intensity of atmospheric mercury pollution in these towns reached the headlines of the media (New York Times, 2011; Siegel, 2011; Howe, 2013; Amalena, 2014) after the publication of the article by Cordy et al. (2011) highlighting that the Department of Antioquia likely occupied "*the shameful first position as the world's largest mercury polluter per capita from artisanal gold mining*".

As a consequence of this dramatic scenario of mercury pollution, UNIDO – United Nations Industrial Development Organization joined forces with CORANTIOQUIA – the Environmental Agency of Antioquia, with the Secretary of Mines of Antioquia, with the Department of Mining Engineering from the University of British Columbia (UBC) and with the School of Mines from the National University of Colombia in Antioquia to start a project to improve the activities of the "entables" and gold shops, focusing on reduction of mercury pollution. The main accomplishments of this project, named **Colombia Mercury Project (CMP)**, are described here.

4. Methodology

4.1. Conduct a balance of mercury in the "entables"

A mercury balance was established to estimate the mercury losses from the "entables". This consisted of measuring (weighing) the amount of mercury introduced into the amalgamation process and that which is recovered by squeezing and retorting (when retorts are used) at the end of the process. This procedure was conducted in 2010, in 15 "entables" in the towns of Remedios and Segovia, as detailed in Cordy et al. (2011). As a result, on average 50% of the mercury introduced in the process was lost: 46% of which was lost to the tailings as mercury droplets and 4% of which was evaporated when amalgams were burned. In some cases, it was observed that up to 82% of the mercury introduced in the "cocos" was lost with tailings. This mercury balance was repeated in 2013 after introduction of the CMP interventions to reduce mercury use and losses. Unfortunately the balance was not repeated in the same "entables". Only 40% of the 15 "entables" sampled in 2010 were part of the 2013 balance. The balance was conducted in 20 "entables" with participation of the "entable" owners and their clients, the miners. All "entables" have been using the same whole-ore amalgamation procedures and have "cocos" with similar dimensions.

4.2. Evaluate atmospheric mercury contamination

Assessment of levels of atmospheric mercury in urban environment was conducted in the towns of Segovia and Remedios in 2010, 2011 and 2012. It was used a portable flameless atomic absorption spectrometer (LUMEX Zeeman Mercury Analyzer RA-915) and opportunistic sampling to analyze mercury concentrations along streets and inside buildings. Frequent mobile transects of urban street concentrations over several weeks in each of the three years of atmospheric study were averaged to assess changes in urban mercury emissions. Transects employed a GPS device and the LUMEX in a vehicle with inlet elevation of 2 m above street level, operated at a target velocity of 20 km/h. Meteorological conditions were roughly similar during each campaign according to nearby weather stations, and production rates were assumed to be

Fig. 3. Fresh (silvery) and gold-loaded (dark) zinc shavings that are evaporated in a furnace.

consistent during the year. Year to year gold production was measured by proxy using increases in milling infrastructure (number of "cocos", gold shops, entables). All results of the air monitoring campaigns were already described in detail by Cordy et al. (2013).

4.3. Assess the health impacts of high levels of mercury in the urban environment

The health assessment was conducted analyzing total mercury levels in urine using the atomic absorption spectrometer (detection limit 2 μg Hg/L) of the Medellin Public Health Lab (LDSP). Mercury and creatinine in urine were analyzed following the protocols described by Veiga and Baker (2004). Clinical assessment and five neuropsychological exams were conducted using the same protocols. This procedure was conducted in 2010 with 50 males from Segovia (ages ranging from 20 to 59, mean: 40.3) occupationally involved in "entables" or gold shops or other mining-related activity. In 2013, urine samples were again analyzed in 37 residents of downtown Segovia not directly involved in mining activities. The ages ranged from 4 to 64 with average of 38.4, and 86.5% were males and 13.5% were females.

4.4. Enforcement and education of miners and owners of "entables"

The main focus of the CMP team intervention was to educate the miners and owners of the "entables" to reduce the amount of mercury entering the "cocos". "Entables" are the primary entry points of mercury into the system. The complete elimination of whole ore amalgamation was not a feasible measure at that time, as the owners of "entables" were not prepared to change entirely their procedures. The CMP strategy was to introduce measures to reduce the use of mercury without significant infrastructure changes and later introducing new equipment to concentrate gold and eliminate the use of "cocos" and whole-ore amalgamation. Education was critical to reduce the use of mercury and ensure sustainability of the suggested measures. This was conducted in each of the 5 target municipalities in Antoquia that focused on community members, miners and owners of the "entables". This included lectures for miners and owners of the "entables" as well as awareness campaigns in the towns impacted by mercury vapour. Demonstration of the use of "activated" mercury and reduction of the speed of the "cocos" were also part of the educational program. Enforcement from the Federal Government through the National Police and the "Procuradoria General de la Republica" (representative of the General Attorney, Mrs Fanny Henriquez) also had a significant effect on changing amalgamation practices.

4.5. Demonstrate how to build gold shop condensers, air filters and retorts

The CMP team started a large campaign to demonstrate and distribute retorts and mercury condensers to "entables" and gold shops in the Segovia-Remedios region, with the aim of popularizing practice of condensing evaporated mercury from amalgams and zinc shavings The main immediate target was to reinforce the point that only retorted gold should be allowed to be melted in towns and even this operation MUST be conducted with good condensers and filters to capture the mercury vapour. The objective was to implement emergency measures to reduce the harmful levels of atmospheric mercury in the urban areas of the towns.

5. Results and discussion

5.1. Health assessment

In 2012, all selected individuals who had urine analyzed revealed levels of total mercury above 100 μg Hg/g of creatinine, which is the level where an individual has high probability of developing clinical symptoms of mercurialism (WHO, 2007). About 24% of these individuals showed tremors, 6% showed muscular aches, 2% had lost teeth, 78% had short-term memory problems (according to an episodic memory test), 24% had visual-motor problems, 8% had problems with space-time orientation and 6% demonstrated audio-attention problems.

According to health studies conducted in 2013 using the classification of Drasch et al. (2002) for levels of mercury in urine, about 43% of the individuals had *normal* levels of mercury (<5 μg Hg/g of creatinine), 35% showed levels in urine above the *action* level (20 μg Hg/g of creatinine) and 16% showed levels above the *maximum* of 50 μg Hg/g of creatinine indicated by WHO (1991) (Table 1). The health authorities of the Department of Antioquia have been conducting monitoring programs in individuals working

Table 1
Total Hg in urine of 37 residents of Segovia in 2013 (levels of toxicity adapted from Drasch et al., 2002).

Level of toxicity	Hg in urine (μg/g creatinine)	% Of individuals
normal	<5	43.24
alert	5–20	21.62
action	20–50	18.92
maximum	50–100	8.11
visible symptoms	>100	8.11

with mercury since 1999 and in 2007 they revealed that 61% of almost 15,000 patients studied had high mercury concentrations (data were not provided) in urine and 16% had very high levels, greater than 35 g Hg/L (Utopia de la Palabra, 2011).

The magnitude of the health problems caused by exposure to medium to high levels of mercury vapour is not fully known, but anecdotal evidence from the medical doctors at the health post in Remedios show an abnormally high incidence of kidney problems that resulted in transplants. Gold shop employees in Antioquia, who are regularly exposed to extremely high levels of mercury vapour, told us that the Antioquia health authorities advised them to take diuretics and stay away from the contaminated sites for one month. When they leave the work place and mercury concentrations in urine come down, they go back to the same polluting activities. In fact, the levels of mercury in urine can be substantially reduced in 30 days but the total mercury elimination through urine can take several years. Mercury levels in urine would not be expected to correlate with neurological findings once exposure has stopped (Veiga and Baker, 2004).

5.2. Enforcement and education

The pressure on the mayors of the 5 municipalities has generated positive reactions on the owners of the "entables" and miners, as they realized they had to move away from whole ore amalgamation for the sake of the health of the town population and their own.

The constant presence of the project trainers at the "entables" provided an environment of mutual respect and trust. In a first step, the trainers implemented two measures that reduced the use and losses of mercury:

1. use of activated mercury
2. reduce the rotation speed of the "cocos"

The miners and owners of "entables" learned how to use "activated" mercury (Pantoja and Alvarez, 2000). Mercury is activated forming sodium-amalgam in an electrolytic process with a 10% NaCl solution. Metallic mercury is connected via a copper wire to the negative pole of a 12-V motorbike battery and the positive pole stays in the solution. "Activated" mercury removes the oxidation layer of the mercury that becomes much more coalescent and forms fewer droplets in the amalgamation process, i.e. less mercury is lost with tailings, and therefore less mercury is used (purchased) by the miners.

Reduction of the "cocos" rotation speed also generates fewer droplets of mercury that are usually lost with the tailings and reduces fugitive mercury vapour from the "cocos". CMP demonstrated to the miners that the "cocos" were rotating above the critical speed,[2] which is the speed in which the ball can be centrifuged inside the mill (Abbe, 2013). Slowing down the mill speed does not sacrifice the gold recovery. In fact, milling 70% below the critical speed increases the effectiveness of the grinding process, which increases amount of free gold available for amalgamation and therefore increases gold recovery. Table 2 indicates the levels of mercury escaping from the "cocos" analyzed with the LUMEX 1 m above the "coco". The analyses were performed in the same "cocos' before and after the CMP intervention. Reduction of around 45% of mercury emissions from the "cocos" were observed.

Numerous community meetings and the actions of the CMP personnel had a positive effect on public awareness about the hazards of mercury vapour, particularly among women. Another positive initiative was the training of miners and owners of "entables" from Antioquia at the UBC (University of British Columbia) demonstration plant in Portovelo, Ecuador, which was established as part of a project sponsored by the US Department of State (Veiga, 2014). The main concept of the training was to convince the "entables" to stop whole ore amalgamation. The demonstration plant included all unit operations to process gold ores. In 4 visits from Aug 2010 to November 2012, 50 Colombian small miners, owners of "entables" and personnel from Gran Colombia Gold observed the evolution of the small-scale gold operations in Portovelo. They also received theoretical and practical classes from the technical team of the UBC project on:

- Grinding for gold liberation
- Gravity concentration using centrifuge
- Flotation of gold and copper minerals
- Oxidation processes for sulfides, including bacterial leaching
- Methods to remove mercury before cyanidation
- Cyanidation and use of activated carbon to extract gold from the solution
- Cyanide destruction with peroxide
- Gold refining with nitric acid
- Chemical analyses of gold and cyanide
- Tailings management
- Water recycling
- Cooperative organization
- Relationship of mining operations with local communities
- Business management

As a result of the visits, 39 small plants were installed in Antioquia following the systems and designs observed in Portovelo: concentration and cyanidation. Due to lack of capital, some plants are still using amalgamation, but only concentrates are processed, which reduces substantially the mercury losses. The spin-off effect of the UBC initiative was outstanding and more miners from Antioquia want to visit the demonstration plant. It is estimated that the implementation of these plants eliminated or reduced the use of **5.1 tonnes/a** of mercury, as assessed in 24 plants implemented in Antioquia. This estimate was based on interviews to the owners of these new plants, in which they were asked how much mercury they were buying before and after the new plants were installed.

Table 2
Comparison of airborne mercury concentrations resulting from milling at a slower speed in different "entables". Fast "cocos" refer to speeds of 54–58 rpm and slow "cocos" refer to speeds near 40 rpm. Results are from the same "cocos" before and after the intervention.

Entable	Hg escaping from fast "cocos" (ng/m^3)	Hg escaping from slow "cocos" (ng/m^3)
1	176,000	86,000
2	262,000	144,000
3	985,000	573,000
4	146,000	95,000
5	54,000	23,000
6	137,000	42,000
Ave	293,333	160,500

5.3. Assessing the amount of mercury used and lost

Whole ore amalgamation was not completely eliminated, however the amount of mercury used was reduced. In 2010, the average amount of mercury introduced into each "coco" was 78.1 g (with around 60 kg of ore) per shift, based on mercury balance in 15

[2] The critical speed of a ball mill is = 42.29/D^{½}, where D is the internal diameter of the mill in meters.

"entables" (Cordy et al., 2011). At the end of 2013, the balance in 20 "entables" in Segovia and Remedios, after the use of "activated" mercury and reduction of the "coco" speed as described above, revealed that the average amount of mercury entering each "coco" changed from 78.1 to 44.3 g (approximately 43% reduction from 2010 levels). Less mercury was entering the system, and more mercury was being recovered (Table 3). The amount of mercury lost in 2010 was 36.1 g/"coco" and at the end of 2013 it was 13.5 g/"coco", indicating a reduction of 63%. Less mercury was also lost with tailings and by evaporation. The ratio kg of Hg_{lost}: kg of $Au_{produced}$ in 2010 was in average 14.6 and it was reduced by 55% to around 6.5 in 2013 (Tables 3 and 4). This result was used by the CMP team to convince the remaining owners of the "entables" to reduce the amount of mercury introduced into the "cocos" without sacrificing their gold production. One of the arguments used was that the mercury losses imply gold losses as well, since the efficiency of the amalgamation is reduced as mercury, along with gold, is pulverized and lost with tailings (Veiga and Baker, 2004).

In 2010 the only mercury recovered (on average 50% of the initial mercury) in the amalgamation process was the excess mercury derived from squeezing the amalgam in a piece of cloth (previously, no one was using any kind of condenser system - retort or filters). In 2013, the squeezing process still recovered the largest amount of mercury (in average 60.5%) but a small part of mercury, in average 8.1%, was recovered by the use of retorts (Tables 3 and 4). This corroborates the Veiga et al. (2014b) assertion that "*the largest amount of mercury lost in an amalgamation process is associated with the amalgamation of the whole ore and not with the thermal decomposition of the amalgams*".

In 2012, through interviews with the miners and local authorities and monitoring changes in gold production infrastructure, the CMP team estimated that the gold production increased 30% (Cordy et al., 2013). In the 2013 mercury balance, most mercury losses were associated with tailings as all 20 "entables" sampled were using retorts and condensers when the study was performed. The mercury escaping from retorts was not quantified, but this is not a significant factor in the mercury balance (Veiga, 1997), even though it likely produces unsafe vapour exposure.

In each year of the CMP activities, airborne mercury contamination exceeding levels of 10,000 ng total Hg/m^3 were observed in front of various "entables", many of which located near schools. The levels of mercury inside some "entables" and gold shops have reached alarming levels of near 1 million ng Hg/m^3 even when amalgam was not being burned. The World Health Organization (2007) estimated a tolerable concentration of 200 ng Hg/m^3 for long-term inhalation exposure to elemental mercury vapour. It is expected to observe symptoms of central nervous system toxicity in individuals exposed for some years to 20,000 ng/m^3 of elemental mercury vapour. The normal atmospheric levels of mercury in a road outside Segovia, was 10–20 ng Hg/m^3 (average of 10 s analyzed by LUMEX), but in the town, almost everywhere, the air had usually concentrations of mercury ranging from 200 to 400 ng Hg/m^3, including inside the city hall of Remedios. Cordy et al. (2013) reported a clear reduction of atmospheric mercury levels in the years 2011 and 2012, during and after the CMP was implemented, in spite of gold production increases during that time.

Considering that 73–110 tonnes/a of mercury was lost in 2600 "cocos" in the 5 municipalities studied in Antioquia in 2010 (Cordy et al., 2011), and assuming approximately 63% reduction in mercury losses, as described above, then between **46 and 70 tonnes/a** of mercury has been prevented from polluting the environment. Mercury losses may still be between 27 and 40 tonnes/a but this must be further investigated since fewer miners are no longer taking their ores to the "entables", and instead are selling them to Gran Colombia Gold and other smaller mercury-free plants being established in the region.

5.4. Demonstrate the use of condensers and retorts

Retorts are usually portable pieces of equipment used to evaporate mercury from amalgams and condense the vapour with air or water coolers (Veiga, 2007). However, there are other types of condenser not as portable as a retort that can be installed on top of fume hoods. Some "entables" adopted a locally made fume hood in which the amalgam is burned with a propane torch and the

Table 3
Mercury Balance in 20 "entables" after interventions of the CMP.

#	Ore per coco (kg)	Initial Hg per coco (g)	Total Hg lost per coco (g)	Total Hg lost (%)	Hg recovered by condenser (%)	Hg recovered by squeezing (%)	Total Hg recovered (%)	Gold produced per coco (g)	Ratio Hg lost: Au produced
1	66.0	56.4	27.1	48.0	10.5	41.5	52.0	6.6	4.1
2	59.0	44.6	20.2	45.3	4.7	50.0	54.7	1.7	11.9
3	67.0	41.7	8.9	21.3	5.0	73.6	78.7	1.7	5.2
4	62.0	48.2	10.0	20.7	4.6	74.7	79.3	1.9	5.3
5	61.0	22.2	12.9	58.1	6.8	35.1	41.9	1.2	10.8
6	68.0	29.2	14.2	48.6	4.8	46.6	51.4	1.7	8.4
7	55.0	38.5	4.8	12.5	1.6	86.0	87.5	0.8	6.0
8	59.0	45.6	9.5	20.8	4.4	74.8	79.2	1.8	5.3
9	60.0	35.5	6.1	17.2	4.8	78.0	82.8	1.6	3.8
10	64.0	65.1	17.4	26.7	4.0	69.3	73.3	2.3	7.6
11	55.0	33.3	13.9	41.7	1.5	56.8	58.3	0.9	15.4
12	58.0	44.0	15.9	36.1	16.1	47.7	63.9	5.9	2.7
13	63.0	49.8	11.3	22.7	4.4	72.9	77.3	2.7	4.2
14	65.0	56.0	19.8	35.4	13.6	51.1	64.6	7.2	2.8
15	58.0	58.0	22.5	38.8	2.1	59.1	61.2	0.9	25.0
16	70.0	44.3	6.8	15.3	21.0	63.7	84.7	9	0.8
17	62.5	26.5	7.1	26.8	7.2	66.0	73.2	1.5	4.7
18	59.0	61.0	10.7	17.5	12.8	69.7	82.5	7.5	1.4
19	64.0	48.0	15.1	31.5	20.6	47.9	68.5	8.9	1.7
20	60.0	38.0	15.9	41.8	12.1	46.1	58.2	4.3	3.7
AVE	61.8	44.3	13.5	31.4	8.12	60.5	68.6	3.51	6.53
STDEV	4.1	11.6	5.9	13.1	6.0	14.2	13.1	2.9	5.7

STDEV – Standard Deviation.
Hg recovered by condenser implies in the mercury vapour condensed in a retort or in a condensing system with filters used by some gold shops.

Table 4
Average results of the mercury balance in 2010 and 2013.

Year	Initial Hg per coco (g)	Total Hg lost per coco (g)	Total Hg lost (%)	Hg recovered by condensers (%)	Hg recovered by squeezing (%)	Total Hg recovered (%)	Gold produced per coco (g)	Ratio Hg lost: Au produced
2010[a]	78.1	36.1	50.0	0	50.0	50.0	2.48	14.6
STDEV	21.2	18.6	14.7	0		14.7	2.0	21.2
2013[b]	44.3	13.5	31.4	8.12	60.5	68.6	3.51	6.5
STDEV	4.1	5.9	13.1	6.0	14.2	13.1	2.9	5.7

[a] Data from 2010 described in Cordy et al. (2011) from 15 “entables”.
[b] Data from 2013, this study, from 20 “entables”.

mercury vapour is extracted by fans to be conducted to a series of air-cooling plastic condensers and then to a plastic barrel filled with fiberglass (Fig. 4a). Even with high condensing efficiency, this fume hood with condensers cannot be used for large amounts of mercury (about 1 kg). Every time an amalgam was burned the exhausted air still showed mercury levels as high as 100,000 ng Hg/m^3.

A retort to condense zinc and mercury when the zinc shavings are burned was also devised and demonstrated. This was basically a steel cover on the top of a furnace in a bath of water surrounding the retort (Fig. 4b). In total, 40 of these retorts were manufactured and delivered to gold shops and “entables”. The mercury balance conducted by analyzing the zinc shaving before and after retorting indicated recoveries of around 90–95% of the mercury. Around **14 tonnes/a** of mercury was recovered (condensed) at sites where the zinc and amalgam retorts were installed.

In the municipality of El Bagre, the CMP team together with the local authorities distributed 150 individual retorts to the miners. These retorts were made with salad bowls acquired in the local grocery shops. Mercury from the amalgam evaporates with a propane torch or in a bonfire and condenses on the cool surface of a glass cover. Wet sand surrounds the cover to avoid fugitive mercury vapours (Fig. 5) (Veiga, 2007). It was not possible to quantify the amount of mercury currently being recovered by these individual miners using salad-bowl retorts.

5.5. Other measures to reduce mercury pollution

Other circumstances also helped the reduction of mercury use:

1. New Colombian Law prohibiting the use of mercury in gold mining
2. Increasing price of mercury
3. Gran Colombia Gold signed contracts with miners

Apprehensions that a **new federal law** would forbid the use of mercury created more awareness on the miners. In fact in July 2013, the Colombian Congress prohibited the use of mercury in gold processing to be effective in June 2018 (Semana, 2013). How effective the enforcement of this law will be and how the artisanal miners will change their techniques remains to be seen. This law together with international regulations on mercury trading has increased the price of metallic mercury. Under pressure from the United Nations, most governments of developed countries have signed a new international agreement to limit mercury trade called the Minamata Convention (Selin, 2013).

Due to the limitations on the accessibility of mercury, the **mercury price is increasing** worldwide. In September 2007, mercury was sold in Antioquia for US$ 35/kg and started increasing until July 2014 when one kg of mercury has been sold for US$ 150. This makes the mercury users more cautious regarding the use and losses of mercury in the amalgamation process. Mercury is simply not as easy or inexpensive to obtain as it was in 2010.

Until the end of 2012, **Gran Colombia Gold** (GCG), a medium size Canadian-based mining company, signed 22 contracts with miners who started selling the ores to the company to be processed (by cyanidation) without mercury instead of using the “entables”. Miners were paid based on sampling and chemical analyses of the ore brought to the company's processing plant. Gran Colombia pays the miners for 55–60% of the gold content in the ore indicated by their analyses. It is important to highlight that in “entables” the gold recovery with amalgamation was less than 40%, and typically as low as 25%. Recently GCG changed their policy and they are paying 45% of the gold content in the ore due to the recent reduction of the international gold price. From 2010 to 2013, this simple procedure resulted in elimination of **15.5 tonnes/a** of mercury that no longer is being used because it has been diverted away from “entables” and into a mercury-free processing plant. Further 55 new contracts with miners are currently in the process of being

(a)

(b)

Fig. 4. Retort installed in gold shops and “entables” for amalgams (a) and for zinc shavings (b).

Fig. 5. Glass-bowl retort made in Colombia.

signed. Projections indicate an additional elimination of **3.8 tonnes/a** in 2014, because of these 55 contracts and 5 other mines that recently signed agreements with GCG. These results were obtained by interviewing the owners of the new plants and asking them how much mercury they buy per month. Some miners still retain 25% of the ore they mine to produce their own gold in "entables". Miners still maintain the perception that they can get quick cash by amalgamation of the whole ore. GCG has been working with these miners to convince them that selling the ore to the company will be more profitable than extracting gold by amalgamation, with the ancillary benefit that they will help reduce mercury pollution.

6. Next steps

The success of the Colombia Mercury Project encouraged the Government of Antioquia and the Ministry of Energy and Mines to invest US$ 6.5 million in the construction of a Training Centre for Miners (conventional and artisanal) in El Bagre and to incorporate training for artisanal miners in 3 other existing vocational centres in Colombia. This initiative will be administered by the National Learning Service (SENA) which is a federal institution dedicated to vocational education of professionals for the industry and commerce. The Canadian International Resources and Development Institute (CIRDI)[3] are working together with SENA to implement this Training Center in El Bagre. The Canadian College of the Rockies and UBC are also in charge of the implementation of a "train-of-trainer" initiative in 3 other SENA facilities in the Northeast of Antioquia. About 30 trainers are being trained to be capable to train artisanal miners on cleaner gold processing and safe mining procedures. This is a concrete and sustainable measure, since projects come and go, but a federal centre will create a more sustainable site to educate artisanal miners. Some ideas have been discussed with the Government of Antioquia and SENA to incorporate not only technical subjects in the training curriculum, but also other courses that can aid the miners in creating a more responsible enterprise. Such courses include: ethics, accounting, business management, economic diversification, health and environmental issues in mining, social responsibility, etc.

7. Conclusion

The success of the Colombia Mercury Project intervention is attributed to the integrated actions of dedicated professionals from international agencies, Government and academy. The project adopted a strategy of educating the owners of the "entables" on cleaner methods to produce more gold consequently reducing the amount of mercury entering amalgamation process. Complete elimination of the whole ore amalgamation was not possible yet, but more "entables" are now being converted into more profitable small cleaner processing plants. Close interaction among the stakeholders involved in the project and ongoing dialogue with the miners were effective in reducing mercury use and losses. The project reduced 43% of mercury entering the "entables" and 63% of mercury losses in the amalgamation process relative to the levels observed in 2010. As the first entry point of mercury is the "entables", mass balances conducted in 2010 and 2013 resulted in estimating that between **46 and 70 tonnes/a** of mercury are no longer being lost to the environment in the five project municipalities of Antioquia (Remedios, Segovia, Zaragoza, El Bagre and Nechí). This was due to systematic strategies that addressed the policy, participation, and personality dimensions of interventions, as well as ensuring optimal presence of project personnel and the patient persistence required to maintain efforts until significant changes were observed. The dramatic reduction in pollution was also observed in the levels of mercury in the urban air reported by Cordy et al. (2013). Demonstration of simple mineral processing procedures such as the reduction of rotation speed of the "cocos", use of activated mercury, use of retorts and condensers in the amalgam decomposition, had strong effect in reducing mercury losses. The participation of the Canadian mining company, Gran Colombia Gold (GCG), buying ore from the miners before being treated in the "entables" was also important in avoiding the ore to be processed by amalgamation in the "entables". It is estimated that this eliminated 15.5 tonnes/a of mercury that were used to amalgamated the whole ore. The owners of "entables" also realized that they could recover much more gold using the cleaner processes taught by the CMP team. This generated 39 new processing plants in the region and consequently reduced the amount of material being amalgamated. These mercury-free plants are also currently producing concentrates of copper minerals and gold that are either sold or leached with cyanide. Policy had clear support from all levels of Governments and a transparent line of actions that had resonance in the political context of the country. All actions were designed and discussed **with** the participation of miners and owners of "entables". The needs of the miners were surveyed before planning (Hilson, 2005; Siegel and Veiga, 2009). The project employed dedicated and carefully selected leaders in the community who served as guides and trainers for the actions undertaken. The constant presence of charismatic trainers and their links with the local communities opened many doors to the acceptance of the recommendations to reduce mercury pollution. This is important to

[3] CIRDI is a coalition of University of British Columbia, Simon Fraser University and École Polytechnique de Montréal.

guarantee that the interventions will be sustainable (Jønsson et al., 2009). A bit of enforcement from the National Police and the General Attorney was also critical to speed up the changes recommended by the CMP team to the owners of the "entables". The experience of the CMP team in Antioquia is a case that can easily be reproduced in other developing countries as long as the expectations are previously discussed with all stakeholders, the interventions have support of local Government and the trainers have a permanent presence in the field. Finally, the project team had endless patience in the face of bureaucracies and the lack of understanding about the project objectives and methodology from many stakeholders. It is important to understand the agenda and motives of all stakeholders before starting the implementation of any intervention program.

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